The large eddy simulation group

The eight LES projects in this group were fundamental in nature and aimed at developing improved LES methodology. There were other applied LES projects reported elsewhere in this volume which consisted of evaluating some variants of the LES methodology for industrial use.

Carati and Wray explored the efficacy of the *time* filtered Navier Stokes equations. The equations are closed using a Leonard type expansion and discarding the higher order terms. The equations have a non-linear dependence on the velocity derivative. It was found that lagging this term in time is sufficient for stable numerical solution. The time filtered Navier Stokes calculations with the Leonard closure apparently did not have sufficient dissipation when applied to the problem of decay of isotropic turbulence. Accordingly, additional spatial filtering was performed and two variants of the dynamic eddy viscosity model were included. The space-time filtered equations did produce slightly improved results as compared to the usual spatially filtered equations.

Lagrangian averaging of the flow equations is physically more appealing than the usual spatial or time averaging. This is because averaging is not performed over the turbulent eddies, and thus some of their spatio-temporal features are preserved. Mohseni *et al.* evaluated the so called α equations or the Lagrangian Averaged Navier Stokes equations in the problem of decay of isotropic turbulence. Although there is some ambiguity in the physical interpretation of the variables being solved for, the results from high resolution computations appear to be competitive with those of dynamic LES. However, the results computed with coarse resolution, typical of those expected of robust LES, were not satisfactory. Apparently, the LANS equations are mathematically better understood than the Navier Stokes equations. Hopefully this can be beneficial in analyzing the deficiencies of the model, which in turn could lead to a new predictive tool for turbulent flows.

Recently several investigators have proposed LES methodologies based on advancing two sets of equations, the customary large scale field and the equation for the small scales. For such approaches to be attractive, one should have the benefit of better subgrid scale models and an efficient algorithm for advancing the equations for small scales. Clearly, this approach is more expensive than standard LES with algebraic models, the question is how much more expensive, and whether novel algorithms can be developed that could take advantage of the small scale structures. Hersant, Dubrulle and Wang evaluated the relative importance of several terms in these equations that require closure using turbulent channel data from DNS. They showed that the non-local terms, also known as subgrid scale cross terms, are dominant especially for high Reynolds number data. However, it is not clear that a more accurate modeling of the cross terms is sufficient for actual LES computations, as experience with the mixed models has indicated.

Three papers in this group report on evaluations of wavelet-based turbulence decompositions. The objective is to conduct LES with the least number of degrees of freedom. The wavelet expansions were shown to be particularly efficient in representing turbulent vorticity fields. Moreover, most wavelets tested were able to extract the deterministic or coherent part of the fields, and the remaining subgrid residual fields were nearly Gaussian. Statistics of Gaussian residual fields are, of course, easier to model. The performance of various wavelet decompositions were evaluated using highly resolved DNS fields: Goldstein *et al.* and Farge *et al.* used forced and decaying isotropic turbulence fields at respectable Reynolds numbers, and Schneider *et al.* used forced and unforced mixing layer fields. In the latter case the flow is dominated by large scale coherent structures, and the wavelet filtering does an impressive job of extracting the coherent part of the fields with about 3% of the wavelet modes. In both flows it is shown that wavelets are more efficient than Fourier modes in capturing the coherent structures embedded in the vorticity fields with the fewest number of modes. It is important to note that all three projects were essentially kinematical studies of the turbulent fields considered, and the efficacy of the wavelet transforms for dynamical LES calculations remains to be determined.

One of the pacing items for LES of high Reynolds number wall-bounded flows is the modeling of turbulence in the vicinity of the wall. In this region turbulence is dominated by small scale vortical structures which require significant computational resources to resolve, and hence for engineering and geophysical applications one resorts to modeling, as opposed to computing, the effect of the inner region on the outer flow LES. At CTR Nicoud had already shown that sub-optimal control theory can be used to deduce wall-boundary conditions that take into account the subgrid scale modeling and numerical errors and produce the correct mean velocity profile. During the Summer Program Baggett *et al.* introduced transpiration velocity boundary conditions as an additional parameter which led to a slight improvement of the results. They also attempted to reduce the streamwise turbulent intensities which were too high in their previous work by including it as a penalty in the cost function. This led to a modest improvement in the turbulent intensity profiles. They also demonstrated that their linear wall model, which was a good fit of their sub-optimal computations, is not very robust when different numerical methods or grid anisotropy are used.

One of the promising applications of LES is in prediction of flow generated noise. Lighthill's acoustic analogy is often used to compute the far-field noise using sources obtained from incompressible computations. Oberai and Wang tested a novel methodology for computation of the far-field noise which uses the surface pressure fluctuations as input to the calculations. They used the data from Wang's LES of a hydrofoil trailing edge. Unfortunately, they discovered that because the formulation is in terms of *apparent* monopoles, it was susceptible to numerical errors. This work is a subject of ongoing investigation at CTR.

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